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Cellular Normal Modes: An Explanation for Alluvium Response to Earthquakes

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SYNOPSIS: The cellular mode concept uses simple physical reasoning to treat the response of soft sediments to earthquake shaking. It assumes that discrete areas of the ground, or "cells", have normal modes of vibration, and that each cell has its own natural frequency of vibration. Evidence indicates that shaking effects often relate directly to cell properties. Thus the 1967 Caracas, 1976 Tangshan, 1985 Mexico and 1989 San Francisco earthquakes have damage patterns, liquefaction patterns and instrumental record features which reflect the response of cellular modes. Since the introduction of the concept in 1974 a range of analytical and numerical techniques have been devised to characterise the cells and their response to earthquake shaking.

INTRODUCTION

It has long been realised that local soil conditions change the amount of damage caused by earthquakes. FitzRoy (1839) commented on damage due to the 1835 Talcahuano, Chile, earthquake, noting that houses on loose sandy soil were destroyed, and some on rock were not. Since that time we have sought as professionals to explain the role of soils (or in some cases, to deny it). We have slowly unravelled and separated the foundation failure and ground shaking aspects, then separated ground shaking into topographic and soil effects. Sekiya (1888) introduced the ideas of spectrum and predominant period of soil. Sieberg (1904) described layers of loose material on rock acting as resonators, and Sezawa and Kanai (1930, 1932) treated the interaction of vertically travelling waves with strata in a four part paper.

These initiatives led to a tacit communal belief system that sought to characterise any flexible sedimentary deposit as having a continuously varying fundamental natural period. The period was to be assigned on the basis of extending the stratigraphy under the site in question infinitely along horizontal planes. The stress-strain character of the sediment was taken to be grossly non-linear on the basis of laboratory tests. There was some uncertainty about how deep one had to go in order to obtain an unmodified input signal.

No distinction was made between extremely flexible fine grained Holocene sediments and older alluvial materials which, while stiffer than the recent fine grained material, were clearly much more flexible than rock. Models were therefore constructed assuming that grossly non-linear materials lay down to bed rock, and assuming a one dimensional characterisation of the medium with no interaction between the orthogonal components of motion. These models were shown to produce tolerable matches between predicted and observed response spectra.

However an earthquake recorded on flexible sediment in 1970 made it quite clear that such a simple minded characterisation is inadequate. The infinite layer formalism implicitly separates orthogonal components of the motion so that for example north-south rock motion has no effect on east-west soil motion. However, the single component of the 1970 April 23 earthquake recorded on the sediments of the Hutt Valley, New Zealand shows bursts of sediment motion which cannot be associated with the corresponding component of rock motion. The earthquake (New Zealand Seismological Observatory 70/221) was of magnitude 4.5, 66 km distant and 7 km deep. This result, referred to in Stephenson (1971), and published in Stephenson (1974b), led the author to realise the importance of direction of motion.

The observation at the same site during the 1973 January 6 earthquake, that the resonant motion of sediment was along a straight line, but in different directions at each of two sediment sites, and was highly correlated between the two sites (Stephenson 1974a), in turn led to the publication of the essential concept of cellular resonant modes of response (Stephenson 1975).

The cellular mode concept was given little attention when first advanced, perhaps because it was presented against the background of the 1971 February 9 San Fernando earthquake which showed few dramatic ground-related effects. In addition, its approach was intellectually wide of the mainstream at the time. However, since the introduction of the concept there has been a move from one dimensional treatments towards more realistic situations, and there has been experimental evidence that resonance occurs with one period characterising a whole region (i.e. modal behaviour). The dramatic ground related effects of the 1985 Mexico City and 1989 San Francisco earthquakes have also altered the intellectual climate so that damage effects due to modes of resonance of flexible ground are now mainstream.

The move away from one dimensional approaches is characterised by the work of Bard and Bouchon (1980), Sánchez-Sesma *et al.* (1988), Lee and Langston (1983) and Jiang and Kuribayashi (1988). The experimental evidence of normal modes is given by King and Tucker (1984).

THE CELLULAR NORMAL MODE CONCEPT

The cellular normal mode concept was introduced and named in an attempt to radically alter the way that people picture the motion of a volume of flexible sediment bounded on all sides by rigid rock. The name "cellular normal mode" was chosen in order to emphasise the view that the natural period of the ground does not vary continuously from place to place, but remains constant within each of a series of enclosed "cells". The boundaries of each cell are determined to some extent by the physical boundaries of the sediment, and there is a strong correlation of resonant motion from point to point within each cell. In simple physical terms, it describes the resonant motion of a bowl of jelly.

The cellular mode concept arose from the observation of resonant motion which was the same at each of two sites, but which occurred along a different direction at each site along straight lines. Figure 1 shows the geographical layout of the area in question. The two sites, A and B, are separated by some 900 m. At site A, firm gravels of alluvial origin are overlain by about 14 m of silts and sands of marine and estuarine origin, while at site B the soft layer is 16 m deep. Figure 2 and Figure 3 show the power spectra for all horizontal accelerations recorded during the 1973 January 6 earthquake, which had a peak horizontal acceleration of about 0.03 g at sites A and B. It is quite clear that the resonant motion at about 2.6 Hz is common to the two sites.

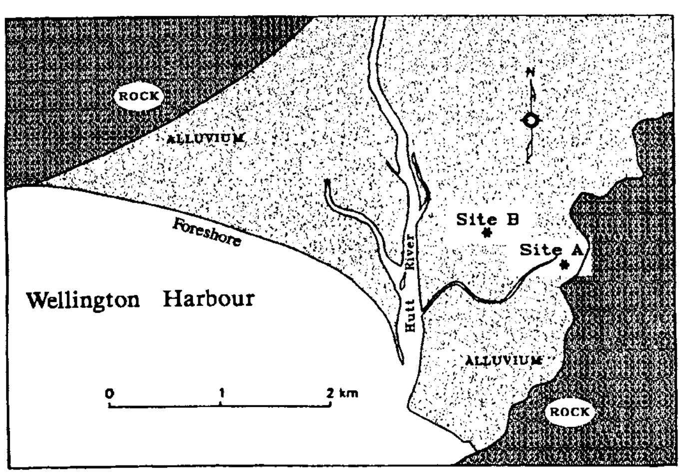

Figure 1. Locations of two strong motion earthquake recorders in the Hutt Valley, New Zealand. Depths of sedimentary material at site A and site B are different, but the same sharp resonance is observed at both sites.

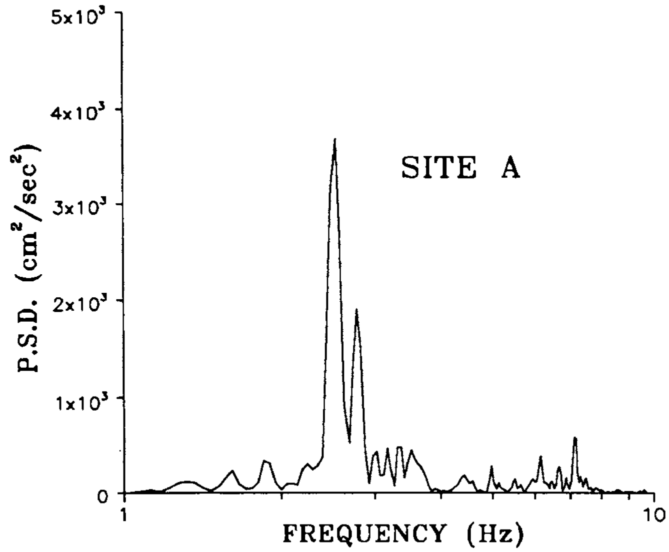

Figure 2. Power Spectral Density at site A, Hutt Valley, New Zealand, for all horizontal accelerations, 1973 January 6 earthquake.

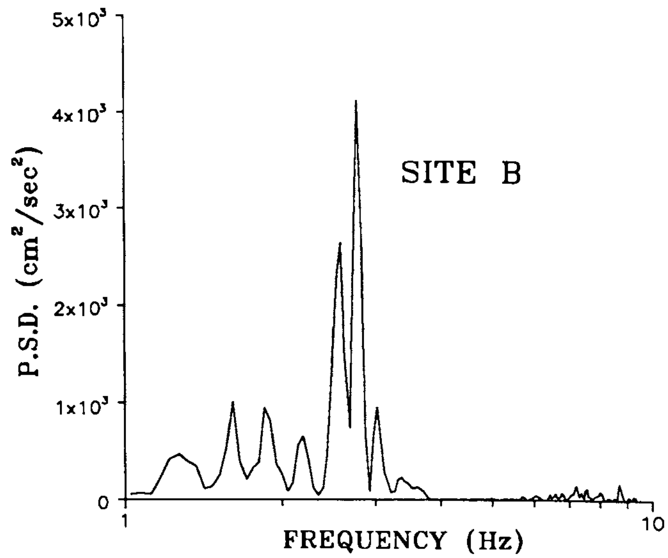

Figure 3. Power Spectral Density at site B, Hutt Valley, New Zealand, for all horizontal accelerations, 1973 January 6 earthquake. Peaks are at the same freqencies seen at site A.

When all the non-resonant motion is removed from the records of horizontal acceleration, and the results presented as polar plots as in Figures 4 and 5, it is seen that the resonant motion has a preferred direction at each of the two sites. These directions are 65 degrees east of north for site A, and 85 degrees east of north for site B.

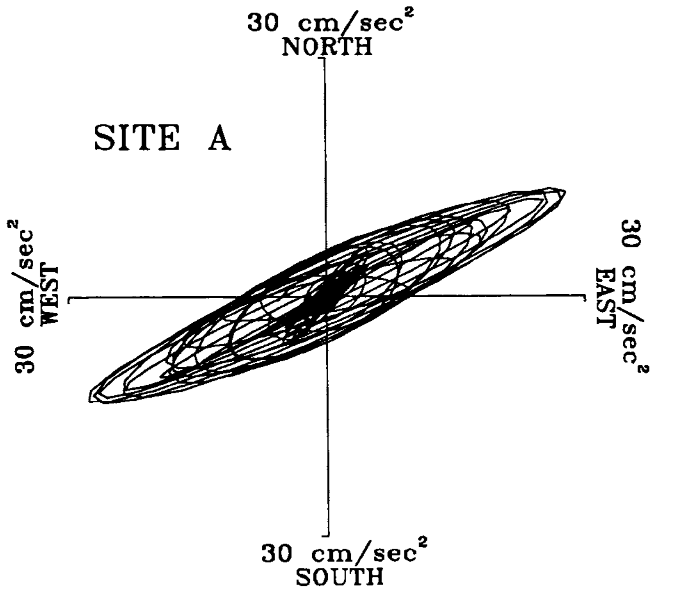

Figure 4. Polar plot of resonant motion at site A, Hutt Valley, New Zealand, for 1973 January 6 earthquake.

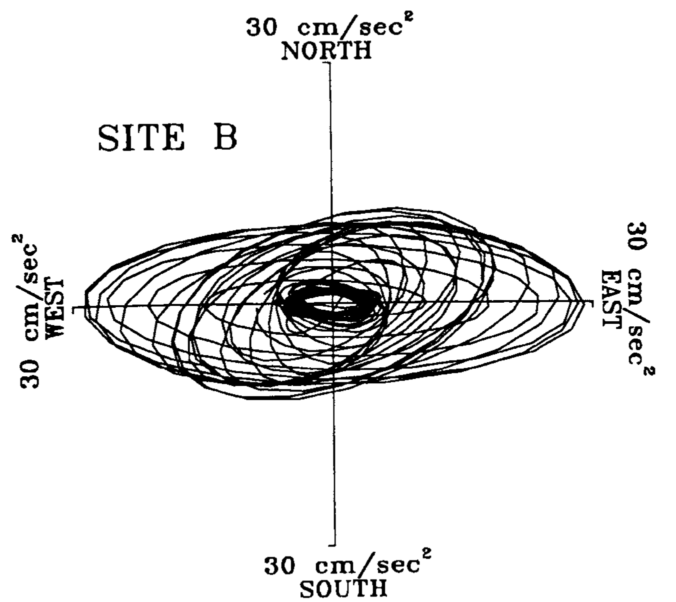

Figure 5. Polar plot of resonant motion at site B, Hutt Valley, New Zealand, for 1973 January 6 earthquake. Predominant direction differs from that at site A.

Finally, when the horizontal resonant motion at each site is resolved along the preferred direction, and the results plotted as time histories as in Figure 6, it is clear that the two motions are nearly the same.

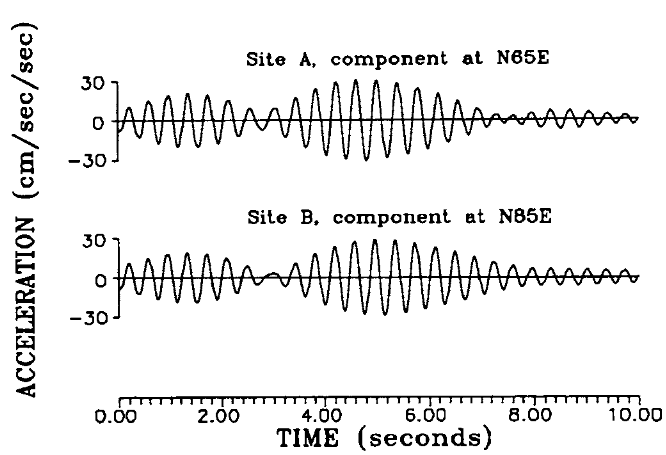

Figure 6. Earthquake motion at both sites, Hutt Valley, New Zealand. Identical motion in different directions at the two sites.

Esteva (1977) interpreted this observation as being a consequence of a torsional resonance. However, while such observations are consistent with torsional motion, they are not necessarily indicative of it. A simple counter-example is resonant motion along an "s" shaped line. The motion at two points along the line would have the required resonant, directional and correlated properties but would involve more than simple torsion.

When considering the nature of normal modes of vibration of flexible sediments, it is appropriate to incorporate both experimental observations and material properties. The motion of such sediments is seen to be mostly in the horizontal plane, an observation which applies particularly in the case of more distant sources. An analysis of the accelerograms in Beck *et al* (1981) and Cousins *et al* (1987) taking all sites which are of sedimentary origin reveals that in nearly half the cases the ratio of peak horizontal to peak vertical acceleration exceeds three. In four fifths of the cases this value is two. When this observed tendency of horizontal motion to dominate is coupled with the high ratio of p-wave to s-wave velocity on recent sediments the essential feature of cellular modes is at once explained. This is a horizontal vector field of acceleration which is solenoidal and oscillatory in time. The observed motion is horizontal, high p to s velocity makes the vector nearly solenoidal (having zero divergence) and resonance implies oscillatory with time.

The formal mode solutions for a cylinder (Stephenson, 1989a) and a hemisphere (Stephenson, 1990a) meet these requirements. Both solutions are also torsional which emphasises the point made earlier that cellular modes can involve torsional motion but need not do so. Figure 7 shows the mode shape for the hemispherical case and gives a clear idea of the deformation shapes of cellular resonant modes.

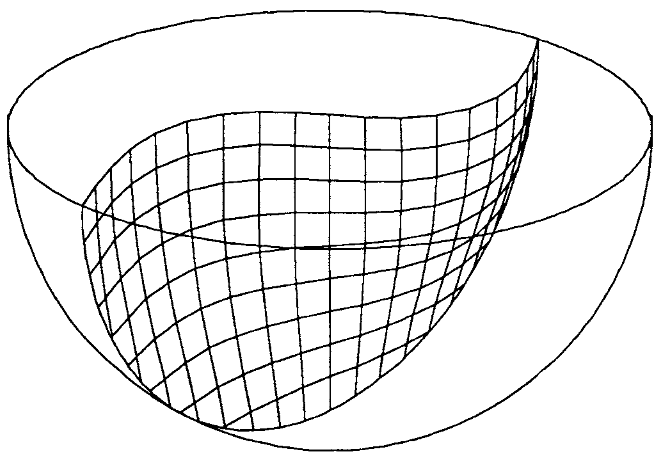

Figure 7. Mode shape for horizontal solenoidal resonant motion of a rigid hemispherical bowl of flexible material.

Such formal solutions together with the axisymmetric finite element models of Stephenson (1990b) characterise the sediment as being linear, i.e. with stress proportional to strain. Provided that the sediment is linear, a full set of normal modes for a cell can rigorously be used as a set of basis functions to describe any motion in the cell. It is clear that a real material such as sediment will not be linear, and in situations of gross ground failure such as liquefaction, that it will be highly non-linear. However there are a number of documented cases where an assumption of linearity introduces no large errors. These are Mexico City, quoted in Whitman (1987), Chusal valley quoted in Tucker and King (1984) and Leukas, Greece, quoted in Stephenson (1975).

USEFULNESS OF CELLULAR MODES

When the incident ground motion contains many cycles of motion at the natural frequency of a cell - typically for a large distant earthquake - the cell will be strongly excited, and damage will reflect the cell properties. The collapse of an automobile factory in Bursa, Turkey, due to low input amplitude shaking to flexible sediment (Tezcan & Ipek 1973); dramatic differences in damage on sediments of differing depth and flexibility in Caracas (Espinosa and Algermissen 1972); differences in damage on and off lake sediments in Mexico City (Marsal, 1958) - all showed dramatic damage due to resonant amplification of quite small incident motion resulting from energy release at some distance from the flexible sites. In these circumstances, when the damage is due to the repeated application of small loads, the response is likely to be more linear rather than less linear, and a mode response is likely to be fruitful.

However, a mode-based approach is less likely to be effective in explaining ground motion in the meisoseismal zone of a large earthquake, when the response of flexible sediments is likely to be substantially non linear as a result of ground failure.

Early undocumented measurements by the author on the sediments of the Hutt Valley, New Zealand, showed that effects beyond those due to simple excitation of independent modes may be quite common. In an extended area which is covered by sediment to a uniform depth, nearly degenerate modes will exist, and these will interact, exchanging energy through the action of small non-linearities in the stress-strain characteristics of the sediment. In such circumstances the cellular mode approach would not correctly predict the details of ground motion (which may in fact be chaotic), but it would indicate a site period. Knowing the site period, planners would be able to insist that buildings of the same period be able to resist abnormally high earthquake loads.

SUPPORTING EVIDENCE FOR CELLULAR MODES

The idea central to cellular mode response is that resonant response will occur, involving the coordinated horizontal motion of a region of sediment. This region may range from a few hundred metres to several kilometres in scale, depending upon the resonant frequency. The response will vary in amplitude from place to place within the cell, and will have an antinodal line of maximum amplitude, which will be a closed loop. Shaking due to response of the cell will be directed along tangents to this line. In any given earthquake the extent of excitation of a cellular mode will depend on the nature of the incident motion. It was shown by Stephenson (1989a) that cellular modes are most readily excited by the transverse component of motion as it sweeps across the cell, with vertically incident waves being ineffective at exciting cellular modes. In addition it is clear that ground motion must be prolonged for several cycles, have the correct spectrum and be non-impulsive, in order to excite the kind of lightly damped resonator that sharp resonance implies.

Given all the above criteria, a sedimentary basin will respond according to the mode shape of the cell, and any gross damage features to uniform structures will reflect the mode pattern. Thus the pattern of sand boils in a uniform deposit of liquefiable sand may sometimes reflect the mode pattern. Damage to uniform buildings or standard structures such as roads, pavements and lamp posts will also show mode patterns in favourable circumstances. In situations where damage details unequivocally show the direction of shaking, this direction will be tangential to an antinodal line.

Instrumental records can also provide evidence as to whether or not cellular modes are a valid description of the motion of sedimentary basis. Various levels of significance apply to the possible ground motion data sets. At one extreme, a dense array of recorders all situated within one cell can be expected to provide mode frequency and mode shape information consistently from earthquake to earthquake. At the other extreme, two widely separated recorders which consistently indicate the same resonant frequency from earthquake to earthquake, and which are within the same geomorphological unit, provide weaker evidence for cellular mode response. Examples of paired resonances are beginning to emerge, but to date a single cell does not appear to have been instrumented. However, an array of eleven ground motion recorders is planned for installation in late 1990 at Pukehou, Hawkes Bay, New Zealand. The site is a 10 m deep peat deposit bounded abruptly by limestone. The peat is roughly 1.5 km across and 2.5 km long, and instruments will be placed at separations of 250 m. Low amplitude results are expected within a short time as the area is within New Zealand's most seismically active region.

Caracas, 1967

Espinosa and Algermissen (1972) present a detailed account of the effects in Caracas of the 1967 July 29 earthquake which was situated some 75 km to the north west of the city. This earthquake is one of the classic examples of soil effects, with great variations in damage occurring.

Espinosa and Algermissen (1972) published a damage map, the essentials of which are shown in Figure 8. The damage appears to lie in a swathe which may be thought of as a segment of a circular pattern some 2000 m in diameter. Various authors have mentioned that damage was most severe to buildings above 10 stories in height, and have assigned such buildings natural periods of around one second. Espinosa and Algermissen recorded and analysed earthquakes at various sites and found that the Brando site (marked with an asterisk near the region of most damage in Figure 8) has a peak at just above one second when its spectrum is compared with the spectrum of motions recorded on nearby rock.

Although there is no evidence that the sediments underlying Caracas have the extreme flexibility of some other sites it is interesting to examine the dimension of a cell with a natural period of one second. Taking the diameter of an optimally excited cell to be a half wavelength in deep material as in Stephenson (1989a), and assuming a shear wave velocity at depth of 2000 m/s, one obtains a diameter of 1000 m for such a cell. Thus the nature of damage in Caracas is not inconsistent with the excitation of a cellular mode in recent sediment by a somewhat remote earthquake.

Hutt Valley, 1968

An essential feature of the cellular mode concept is that the resonant sediment motion will be correlated in a region even though it will be in different directions at different points. A qualitative argument presented by Stephenson (1989a) suggests that it is the transverse component of rock motion which excites the resonance. The 1968 December 1 Cook Strait earthquake, of magnitude 5.4 and situated 30 km from the soft sediment of the Hutt Valley, generated strong motion accelerograms both on the sediment and on a rock outcrop some 300 m from the sediment recorder site. Both accelerograms had a few cycles of motion of about 0.1 g amplitude. Stephenson (1989b) was able to show that the

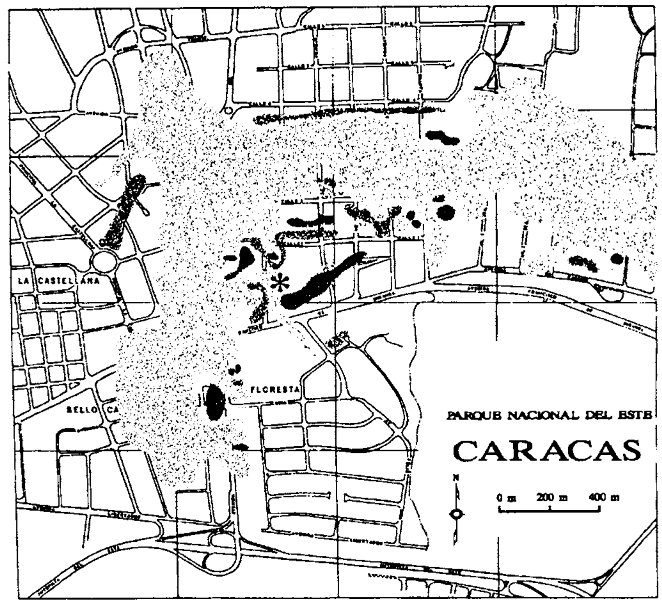

Figure 8. Damage pattern in Caracas, 1967, after Espinosa and Algermissen (1972). Denser shading indicates greater damage. Damage is along the arc of a 2 km diameter circle. Asterisk is the Brando site at which a 1 Hz resonance was observed.

dominant resonance at 2.15 Hz occurred along a direction which is parallel to the rock-sediment boundary, but that the resonance was excited by the transverse component of rock motion. These two directions differ by 25°.

The evidence that transverse motion excited the resonance is particularly compelling. The incoming transverse rock motion had a unique spectral component on the skirt of the resonant response, and this peak was passed to the sediment motion. Simple modelling showed that less than 6% of the resonant response could have been excited by the longitudinal component of rock motion.

Tangshan, 1976

Wang *et al.* (1983) give an account of liquefaction shown in aerial photographs of the Dou river immediately after the 1976 July 28 Tangshan earthquake. Their paper eschews the normal approach of considering material properties, shear stresses and pore pressures in favour of studying the morphology of patterns of sand boils. The supporting theory interprets the patterns as indicating standing waves. Normal modes and standing waves are synonymous, and evidence of standing waves in circular patterns with diameters of a few tens of metres to a few hundreds of metres would constitute evidence supporting cellular modes of response.

It is well documented, e.g. Franks *et al.* (1989), that patterns of sand boils can show patterns of pre-existing liquefiable materials laid down by old river channels, so supporting evidence in favour of cellular modes would require uniform liquefaction potential over a wide area.

Wang *et al* (1983) published aerial photos, but these were degraded by the publication process, only vague patterns being discernable, so that the authors' descriptions must be relied upon. They observe "sandboils in the group of river bends form one or several tortile figures. At one site tortile patterns often rotated in the same direction. At the centre or axis of rotation, sandboiling tends to diminish". Wang *et al* give the outer diameter of these patterns as 500 to 1000 metres.

The shear wave velocity in the sediments is given as 160 m/s, and the computed natural period of the ground 0.25 seconds. In this situation, assuming a shear wave velocity at depth of 2 km/sec, the half wavelength at depth and hence the diameter of the cells would be 250 m. A lower resonant frequency due to either non linear effects or the action of deeper materials would increase this diameter into the observed range.

The patterns as described constitute evidence which supports the concept of cellular modes of response.

<u>Mexico City, 1985</u>

Records made in the Tlahuac region of Mexico City during the 1985 September 19 earthquake have resonant peaks common to two sites, Bombas (TLHB) and Deportivo (TLHD). The site locations are shown in Figure 9, and according to Seed *et al* (1987) TLHB is sited on 105 m of sediments with shear wave velocity less than 115 m/s, and TLHD on 65 m of sediments with shear wave velocity less than 150 m/s.

These two sites, separated by 3.2 km and having very different ground conditions, would conventionally be expected to have substantially different responses to earthquake shaking. Yet the three common resonant peaks of Figures 10 and 11, at 1.9, 3.6 and 5.5 seconds, provide evidence that the two sites are part of the same physical system. The combined shear wave character of all the sediment in the area has apparently given rise to several normal modes of the whole valley system, and the two sites which lie within the system naturally show indications of residing in different parts of these whole-valley modes.

In situations such as this, when the horizontal extent of the resonant system is very much greater than its depth, it is expected that there will be many possible modes of vibration with frequencies close to the fundamental mode frequency. Some of these modes may not be easily excited by direct effects of the incident waves, but will eventually become excited by coupling to the most readily excited mode. The net result will be a complex ground motion arising from the exchange of energy between various nearly degenerate modes which will respond in different directions at different phases. A similar process is documented for pendula by Tritton (1986) and he describes the resultant motion as chaotic.

A polar plot of the resonant motion for the 1.9 second peak at TLHD is shown in Figure 12. It has features reminiscent of that shown by Tritton (1986) and is typical of results for all the TLHB and TLHD resonant peaks.

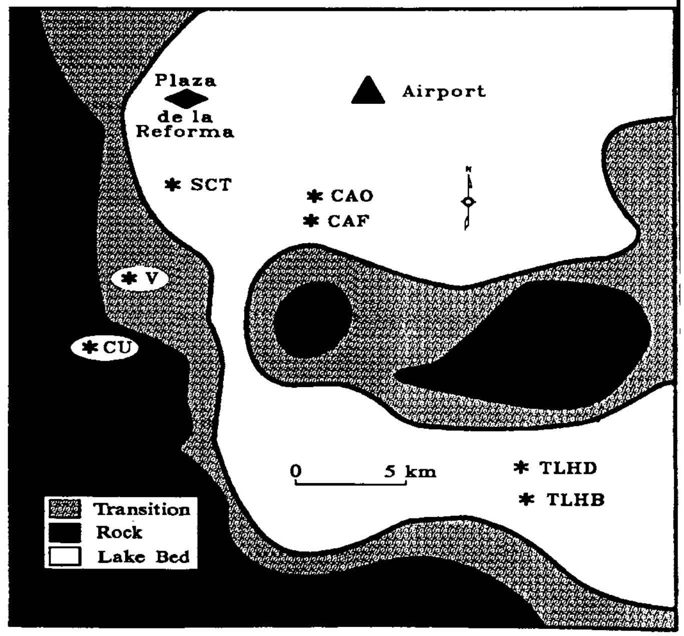

Figure 9. Strong motion seismograph stations in Mexico City. Site conditions at TLHD and TLHB are very different, yet identical resonances are seen despite the 3 km site separation.

Motion of the sort recorded at TLHB and TLHD is what would be expected on the basis of cellular modes being excited by the earthquake. Because of the extent of the sediment a complex interaction between nearly degenerate modes is seen.

<u>Marina district, San Francisco, 1989</u>

During the 1989 October 17 Loma Prieta earthquake, structures 100 km from the source region, on the flexible sediments of the Marina district of San Francisco were greatly damaged in contrast to undamaged structures on nearby firm soil. Two schools of thought prevail on the reasons for this damage, each blaming the sediments in a different way. One school holds that extremely susceptible sands liquefied, and that the foundation disturbance caused by the liquefaction led to structural damage. The other school holds that the flexible nature of the sediments led to amplification of the shaking, and that the resultant more violent shaking caused liquefaction as well as directly damaging structures.

When the damage records of Seekins *et al* (1990), summarised in their Figure 1, are examined it is seen that most damage was not associated with liquefaction. Seekins *et al* are adamant in their preliminary view that "a large part of it" (the damage) "was probably due to shaking alone". They also note a C-shaped zone where the damage is especially concentrated, which does not lie on liquefiable material.

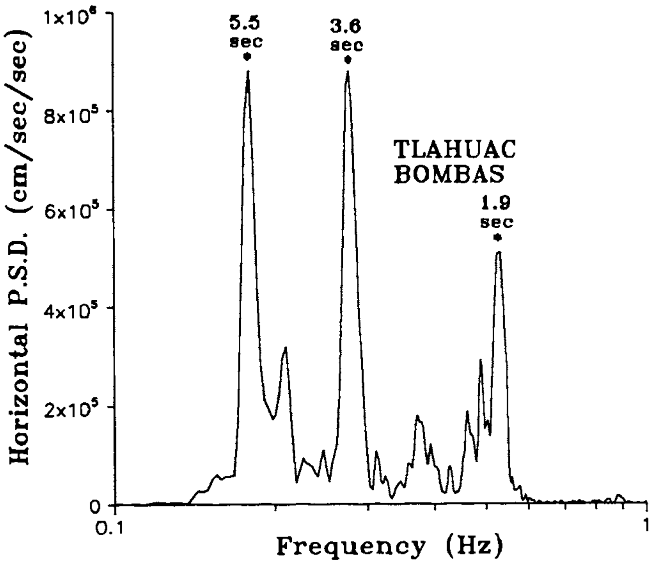

Figure 10. Power Spectral Density of horizontal acceleration at TLHB site, Mexico City. Three prominent resonant peaks are marked.

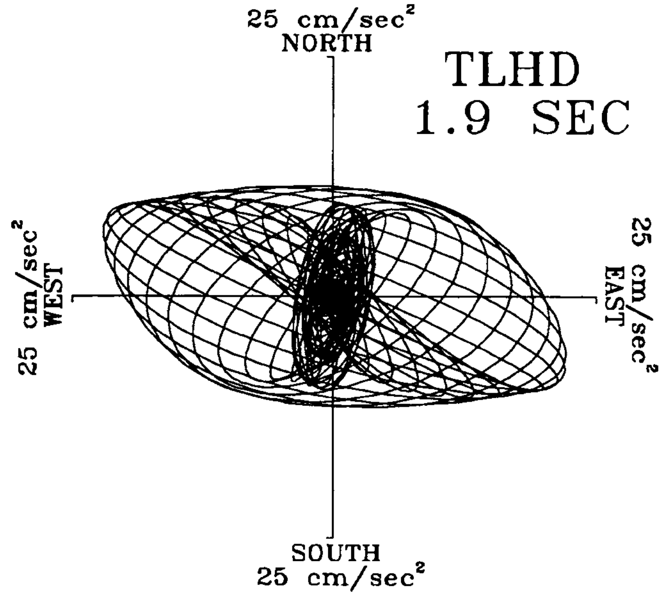

Figure 12. Resonant motion at TLHD site for the 1.9 second peak, 1985 earthquake. The nature of the pattern suggests interaction of nearly degenerate modes.

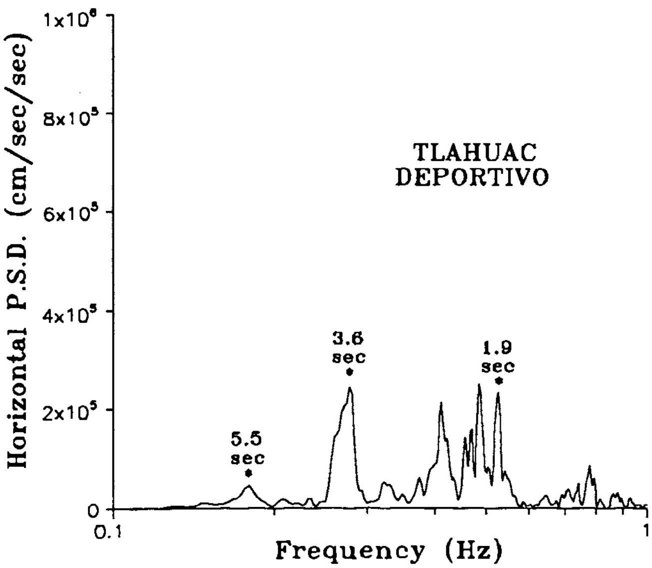

Figure 11. Power Spectral Density of horizontal acceleration at TLHD site, Mexico City. Marked peaks are the same as those in Figure 10 despite the sediment being thinner and stiffer, and the sites being 3 km apart.

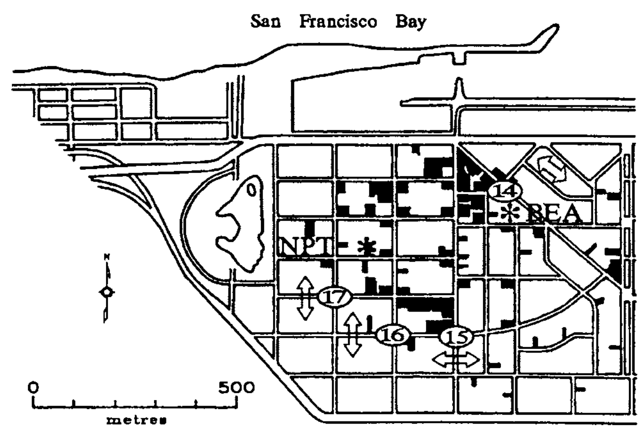

Figure 13. Damage in Marina district, San Francisco, due to 1989 earthquake, after Seekins *et al.* (1990). Red and/or yellow tagged buildings are shown shaded. Asterisks at NPT and BEA indicate USGS aftershock stations. Numbers refer to damage photos shown in next four figures. Broad arrows show shaking directions deduced from damage photos. The overall picture is one of shaking tangential to a circle 500 m in diameter.

The C-shaped zone has a diameter of 500 m. This pattern of damage is reproduced in Figure 13, together with the locations of the seismic stations BEA and NPT and directions of shaking inferred from damage details noted by the author.

Kayen *et al* (1990) show about 12 m of flexible material overlying Pleistocene Bay Mud. They also report a shear wave propagation time of 80 ms through this 12 m of material. Such a layer would resonant at 3 Hz and indeed Figure 6 of Boatwright *et al* (1990) shows a peak at about 2.5 Hz for the BEA and NPT sites. For a shear wave velocity of 2000 m/s in deep material the optimum half wavelength cell size is 400 m.

In four cases of damage, shown in Figures 14 to 17, it was possible to deduce the dominant direction of shaking. In each of the cases the structure had a weak direction and a strong direction, but failure had been along the strong direction. Thus there must have been little shaking along the weak direction. These directions are shown in Figure 13 labelled with the associated figure numbers of damage photos.

Damage in Marina is thus shown to be consistent with the excitation of a simple cell. Both the damage pattern and direction of shaking support this contention. It is expected that an analysis of aftershock records at BEA and NPT will show correlated resonant motion at about 2.5 Hz directed tangentially to the damage pattern at each of the two sites. At the time of writing these records were not available but an analysis is expected to be completed by the time of the conference (March 1991).

ANALYTICAL STUDIES

The common observation that the earthquake generated motion of flexible sediment is predominantly horizontal, together with the knowledge that p-waves travel much faster than s-waves in these materials, led to the observation of Stephenson (1975) that a rational basis for modelling modes of such materials is to assume a horizontal solenoidal vector field. Any axisymmetric horizontal vector field is automatically solenoidal, decreasing the complexity of the solution for a whole subset of problems.

Figure 15. Marina district, San Francisco, October 24, 1989. View south west from junction of Scott and Alhambra showing damage due to shaking along Alhambra.

Figure 16. Marina district, San Franciso, October 24, 1989. View north east from junction of Divisadero and Francisco, showing damage due to shaking along Divisadero.

Figure 14. Marina district, San Francisco, October 24, 1989. View north east from junction of Prado and Cervantes showing damage due to shaking along Cervantes.

Figure 17. Marina district, San Francisco, October 24, 1989. View north from junction of Broderick and Bay, showing damage due to shaking along Broderick.

There are two cases for which analytical solutions are obtainable in terms of well known functions. Stephenson (1989a) gives solutions for cylinders in terms of Bessel functions. Stephenson (1990a) gives a solution for a hemisphere in terms of spherical Bessel functions. In both these cases the medium has been assumed homogeneous and incompressible (in terms of wave phenomena rather than consolidation). The discussion of the cylindrical case includes a qualitative account of the excitation of the modes and concludes that it is the transverse component of the excitation in the underlying rock which excites the normal modes of the sediment. In addition, Stephenson (1990b) has implemented finite element solutions for the general axisymmetric case. A typical finite element mesh and solution are shown in Figure 18. Two general patterns are discernable in the finite element solutions, both reflecting the tendency of the fundamental frequency to take the lowest possible value. Firstly, the period of the fundamental mode is overwhelmingly determined by the deepest, most flexible part of the sediment. Secondly, any thinning or stiffening of the sediment near the edges of the sediment results in a decrease of the mode response at the site of the thinning or stiffening, but little change to the fundamental period.

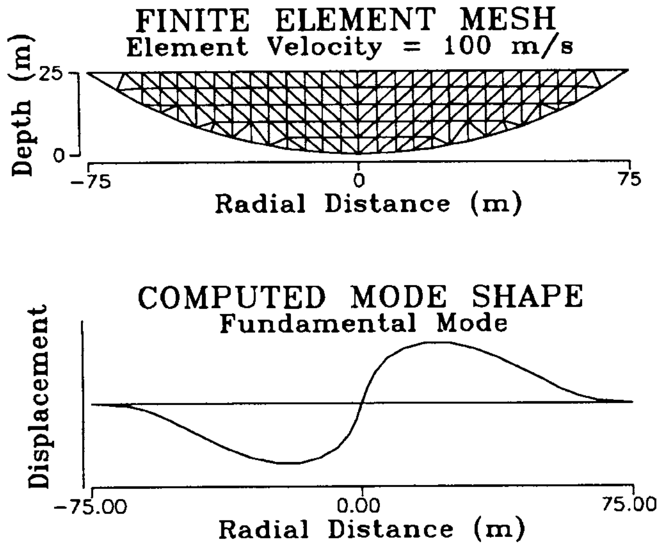

Figure 18. Finite element mesh and resultant mode shape for an axisymmetric finite element model.

FUTURE TESTS

The most distinctive claim of the cellular mode hypothesis is the prediction of correlated resonant motion having different directions within a relatively small area of flexible sediment even when the sediment has different depths at different places. Because of this, a convincing test can only come from an array of a substantial number of recorders which are all located within a small area. Spectral effects would have a large role in determining the response of such an array. A small local earthquake would be expected to be both impulsive in nature and high in frequency, making non resonant effects dominant. However, using records from larger more distant events or recording velocity rather than acceleration would bias the spectrum to lower frequencies, making resonant effects dominate. It is highly likely that this is why distinctive damage patterns on flexible sediment develop for large distant earthquakes rather than small local ones.

Although the array investigations outlined above can provide definitive evidence of the existence of cellular modes, the reality is that such arrays do not yet exist. However there is a large body of other data which can provide more circumstantial evidence for cellular modes. Any site on flexible sediment which consistently provides evidence of resonance at a particular frequency along a particular direction supports the concept and is a candidate site for the installation of more recorders.

Excitation by the transverse component of rock motion is another feature of cellular modes. Sediment sites which have nearby rock sites could be used to provide more circumstantial evidence along these lines. A constant ratio of the resonant spectral ordinate for transverse rock motion, to the resonant spectral ordinate for all horizontal motion would support cellular modes. For this type of analysis all horizontal directions should be used for the sediment motion to allow the possibility of mode coupling. Power spectra are appropriate to allow the addition of effects in different directions. Earthquake origins of differing azimuths should be treated with caution because the rock to sediment coupling could be a function of epicentral azimuth.

CONCLUSIONS

The cellular mode response hypothesis was put forward in 1974 but attracted little notice. The passage of sixteen years has seen thinking move in directions much more in line with the hypothesis. Damage patterns observed in the 1967 Caracas earthquake and the 1989 Loma Prieta (San Francisco) earthquake strongly support cellular mode response. Liquefaction patterns in the 1976 Tang Shan earthquake also appear to support the idea. Instrumental records from Mexico City made during the 1985 earthquake show correlated resonant motion between geotechnically distinct sites with a wide separation and are consistent with an interaction between cellular modes. A pair of accelerograms from the Hutt Valley, New Zealand, shows the importance of the transverse component of rock motion in exciting resonant modes of sediment. First steps have been taken to establish a numerical basis for the treatment of cellular resonant modes.

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